How limiting transpiration under high evaporative demand can improve wheat yield in current and future climate scenarios

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Introduction

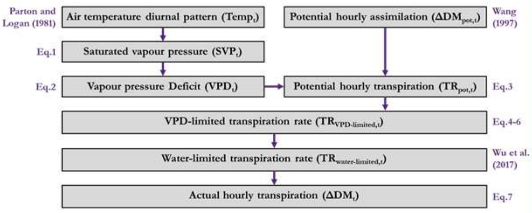
Transpiration efficiency (TE) appears a promising mechanism to increase yields in drought-prone environments where crops rely heavily on soil water[2,3,6,9].

One approach to select for enhanced TE under water-deficit conditions is to identify genotypes with reduced stomatal conductance (reduced transpiration and assimilation) at elevated VPDs, which allows conservation of soil water. The conserved water early in a season can support crop physiological activity at later stages[3,4,6].

In this study, the potential of breeding for limited transpiration at high VPDs and higher transpiration efficiency was explored across the Australian wheatbelt.

A new transpiration module

A new module was developed for APSIM-NextGen[11] improved for canopy development[12]. Based on the SPASS[2] model, this module simulates hourly transpiration rate and biomass assimilation as follows:



(Eq.1) $SVP_t = 6.1078 \times \exp(17.269 \times Temp_t / (237.3 + Temp_t))$

(Eq.2) $VPD_t = 0.1 \times (SVP_t - SVP_{Tmin})$

(Eq.3) $TR_{pot,t} = \dfrac{\Delta DM_{pot,t} \times VPD_t}{TEc}$ (sunrise $\leq t \leq$ sunset)

(Eq.4) $TR_{refVPD} = \dfrac{\Delta DM_{pot,refVPD} \times VPD_{ref}}{TEc}$

(Eq.5) $Reduction_t = Max(0, TR_{pot,t} - TR_{refVPD}) \times \alpha$ (for VPDt>refVPD)

(Eq.6) $TR_{VPD-limited,t} = TR_{pot,t} - Reduction_t$

(Eq.7) $\Delta DM_t = \dfrac{TR_{water-limited,t} \times TEc}{VPD_t}$

t : time (hour),
$Temp$: hourly temperature (°C)
SVP : saturated vapour pressure (hPa)
ΔDM_{pot} : hourly potential increase in dry matter ($g.m^{-2}$)
TEc : transpiration efficiency coefficient ($kPa.gC^{-1}.m^{-2}.mm^{-1}$),
TR_{pot} : potential transpiration (mm)
VPD_{ref} : VPD above which transpiration rate reduces (kPa),
TR_{refVPD} : transpiration rate at VPD_{ref} ($mm.hr^{-1}$),
$\Delta DM_{pot,refVPD}$: interpolated hourly growth at VPD_{ref} ($g.m^{-2}$),
α : level of transpiration reduction when VPD>VPD_{ref} (decimal),

$TR_{water-limited}$: hourly transpiration limited by soil moisture (mm).

Water-limited transpiration ($TR_{water-limited}$) is calculated by capping $TR_{VPD-limited}$ starting from maximum $TR_{VPD-limited}$ at midday until total extractable soil moisture can meet crop daily demand.

The performance of this module was evaluated at five experiments in Gatton where cv. Hartog was cultivated with different irrigation regimes, N application rates, stubble managements, row spacings, and planting dates.

Simulation setup

Five sowing dates, five initial soil moisture levels and local N application rates were adopted from[5] for 60 locations. Simulations were run for cv. Hartog (no transpiration-VPD response), and two virtual genotypes with a 30% (Hartog30) and 100% (Hartog100) reduction in transpiration rate when hourly VPD >1.3kPa (Chenu, unpublished) under current climate (1988-2017) and a climate scenario representing the period 2036-50 (weather data over 1976-2005 adjusted with $[CO_2]$=541ppm, 10% reduction in precipitation, 1.6 and 2°C increase in daily minimum and maximum temperatures; Ababaei and Chenu, unpublished). Under current climate, atmospheric CO_2 concentration was adopted from[7].

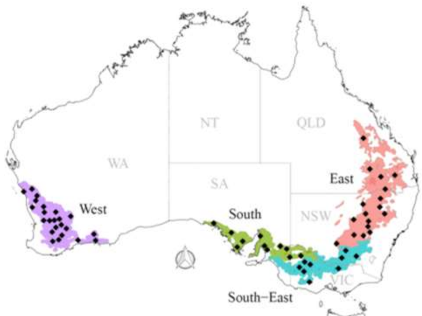


Figure 1: The Australian wheatbelt and 60 selected sites in four major wheat-producing regions.

Results

APSIM-NextGen performance with the new transpiration module

APSIM-NextGen with the new transpiration module performed relatively well across the range of conditions tested (Figure 2). In-season LAI and biomass and final grain yield were better reproduced with the new module than without it (data not shown).

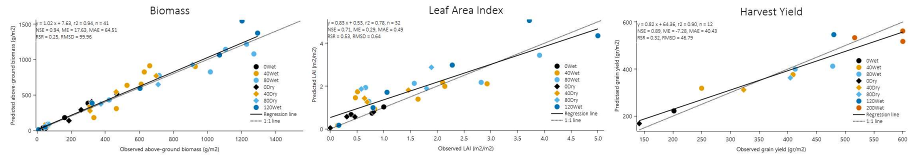


Figure 2: Simulation of in-season biomass (left), leaf area index (LAI; middle) and grain yield (right) by APSIM-NextGen (with improved canopy growth and development) and new transpiration module at five experiments in Gatton, Australia. In the legends, the numbers depict amount of N applied (in $kg.ha^{-1}$) under full irrigation (wet) and rainfed (dry) conditions.

Impact of reduced transpiration rate at high VPDs

The regional average yield (and TE) gains in the East, South-East, South, West and nationwide were estimated to be 1.8 (2.6), 0.4 (1.1), 0.7 (1.1), 0.7 (1.3) and 1% (1.5) for Hartog30, and 4.4 (11.6), 1.5 (6.5), 2.5 (4.9), 2 (5.5) and 2.9% (6.8) for Hartog100 (Figure 3a).

Largest yield gains due to water-conservation were simulated in Queensland and New South Wales where crops often rely heavily on soil moisture (sites with PAWC in Q4; see Figure 3a-b caption).

With Hartog100, yield loss >5% where only simulated in 15% of the site×season combinations, mainly in the West.

Positive yield gain was simulated in 61.5 and 55.3% of the seasons under current climate, and 67.3 and 66.2% under future climate for the two virtual genotypes Hartog100 and Hartog30, respectively (Figure 3c).

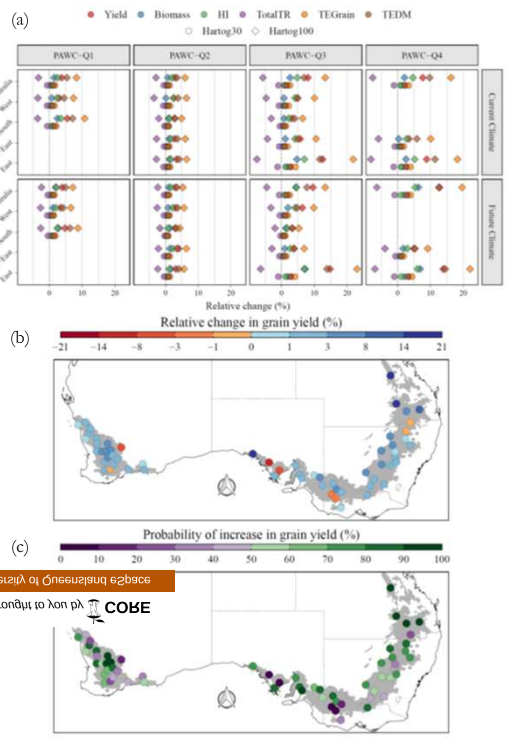


Figure 3: (a) Relative change in wheat yield across the wheatbelt for four quartiles (Q1-4) of plant available water content (PAWC), under current and future climate, **(b-c)** average yield gain and probability of yield gain when limiting transpiration rate at high VPDs in Hartog100 under current climate. HI: harvest index; TotalTR: total transpiration; TEGrain and TEDM: TE in terms of yield and biomass.

Conclusions

- **Limiting transpiration rate at high VPDs appears a promising trait to increase yield** … **crops heavily rely on soil moisture.**
- **Positive impact of the trait is expected to be larger under drier and warmer future climate.**

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